A

TEXT-BOOK OF PHYSICS.

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SOUND.

WITH 85 ILLUSTRATIONS.

EIGHTH EDITION

LONDON
CHARLES GRIFFIN & COMPANY, LIMITED
EXETER STREET, STRAND, W.C. 2
1922

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TEXT-BOOK OF PHYSICS.

SOUND.

PREFACE TO EIGHTH EDITION.

It is gratifying that the seventh edition of this work has been so quickly exhausted and that the demand for copies continues so constant. The sixth edition received most careful revision, and this reprint is issued to fill orders.

September 1922.

PREFACE TO FIFTH EDITION.

A NUMBER of alterations have been made in this edition, some of them to remove difficulties and errors which have been kindly pointed out by readers, to whom we desire to express our hearty thanks. A few additions have been inserted. The Theory of Combination Tones, due to Helmholtz, described in Chapter X., has in previous editions been advocated as probably sufficient to account for the observed facts. In this edition it is recognised that the evidence is far from complete, and a more cautious attitude is adopted.

November 1908.

PREFACE.

THE following account of the phenomena of Sound and of the theory connecting them together forms one part only of a Text-Book of Physics which the authors are preparing. The Text-Book is intended chiefly for the use of students who lay most stress on the study of the experimental part of Physics, and who have not yet reached the stage at which the reading of advanced treatises on special subjects is desirable. To bring the subject within the compass thus prescribed, an account is given only of phenomena which are of special importance, or which appear to throw light on other branches of Physics, and the mathematical methods adopted are very elementary. The student who possesses a knowledge of advanced mathematical methods, and who knows how to use them, will, no doubt, be able to work out and remember most easily a theory which uses such methods. But at present a large number of earnest students of Physics are not so equipped, and the authors aim at giving an account of the subject which will be useful to students of this class.

Even for the reader who is mathematically trained, there is some advantage in the study of elementary methods, compensating for their cumbrous form. They bring before us more evidently the points at which the various assumptions are made, and they render more prominent the conditions under which the theory holds good. For such readers the authors hope that this work may afford a fitting introduction to more advanced treatises, and especially to Helmholtz's great work, *The Sensations of Tone*, which deals chiefly with the physiological aspect of Sound, and to Lord Rayleigh's *Theory of Sound*, at once the most systematic, original, and complete work on the subject.

January 1899.

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CHAPTER I.

THE NATURE OF SOUND AND ITS CHIEF CHARACTERISTICS.

CONTENTS.—Origin of Sound and Sound-Waves—Characteristics of Waves—Characteristics of Sounds—Loudness—Pitch—Quality—Sound-Waves are Longitudinal—Noise.

THE sensation which we receive through the ear, and the external disturbance which arouses that sensation when it reaches the ear, are both denoted in common language as sound. In physics we are concerned with the external disturbance, and our aim is to investigate the conditions under which it arises, the mode in which it is propagated from its source, and the variations in the nature of the disturbance which correspond to the differences in the sensations we experience.

Sound arises in general from Vibrating Sources.—An examination of the mode of sounding any musical instrument in which the sounding parts consist of strings, rods, or bars, shows that these are always struck or pulled in such a way that they are set in vibration. Usually the vibration is so frequent that we cannot follow the motion to and fro, though it may be so wide in extent that the outline of the vibrating body is visibly altered. More generally, when any body, whether designed as a musical instrument or not, is set in vibration, if the vibrations are regular and of sufficient frequency and extent, a musical note is heard. Instances, such as a tumbler or a gas globe, will occur to the reader.

A Vibrating Source gives rise to Waves in the surrounding Air.—Let us imagine a round, flat, metal plate hung up by strings (Fig. 1, *a*) passing through holes bored at a suitable distance—about 0·68 of the radius is the best—from the centre. When struck at the centre, it vibrates between the positions shown by the dotted lines in Fig. 1, *b*, the central part always moving to and fro in the opposite direction to the rim, and the circle through the suspending holes being at rest. Considering only the central portion, we can see how its vibrations will affect the air. As the plate moves forward it pushes against the layer of air in front of it, compresses it, and drives it against the next layer. This next layer is then compressed and pushed forward against the next, and so on, the push being transmitted on through the air. When the plate has reached the limit of its forward excursion it returns, and the air follows it, expanding into the space vacated by the plate. This relief of pressure has the same effect as a pull, and therefore we may think of the plate as now pulling at the layer of air in front of it. As this layer moves backwards it lessens the pressure against the next layer, which also moves backwards, and so on. Thus, the extension or pull of the air is transmitted forwards after the push. When the plate makes another forward motion, another push is sent out, to be followed, when the plate

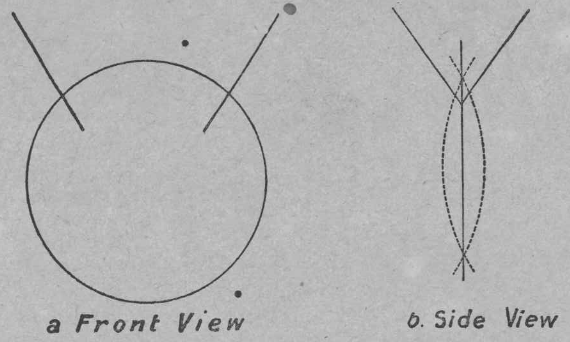

Fig. 1.—*a.* Vibrating Plate hung up by strings through points 0·68 radius from the centre.
b. Dotted lines showing the mode of vibration when struck at the centre.

returns, by another pull. These pushes and pulls, or compressions and extensions, with the necessary to-and-fro motions, constitute air-waves, each complete wave consisting of a push and a pull. To obtain a clear notion of the movement of the layers of air during the propagation of the waves, the reader should construct a Crova's disc like that represented in Fig. 2. Eight or ten equidistant points are taken on a small circle at the centre of a large card, and from these points, taken as centres in regular succession, circles are drawn, with radii increasing successively by a constant amount greater than the distance between the successive centres. Fifteen or twenty circles may be thus drawn, and if the card is rotated about its centre, the motion of the curved lines on one side of the centre will represent the to-and-fro motion of the layers of air, as this would appear if we could suppose the air visible and watched by an observer on one side of the line of propagation. If the circles are drawn on a small scale and nearly up to the centre, as in Fig. 2, it is better to cover up the card with a second fixed card having a slit cut in it, say of the width shown by the dotted lines, so that the curved lines are only seen through this slit and their curvature is less evident. But with a large disc this is quite needless.

We shall now briefly consider the evidence which leads us to believe that the waves arising from the vibrating source constitute sound.

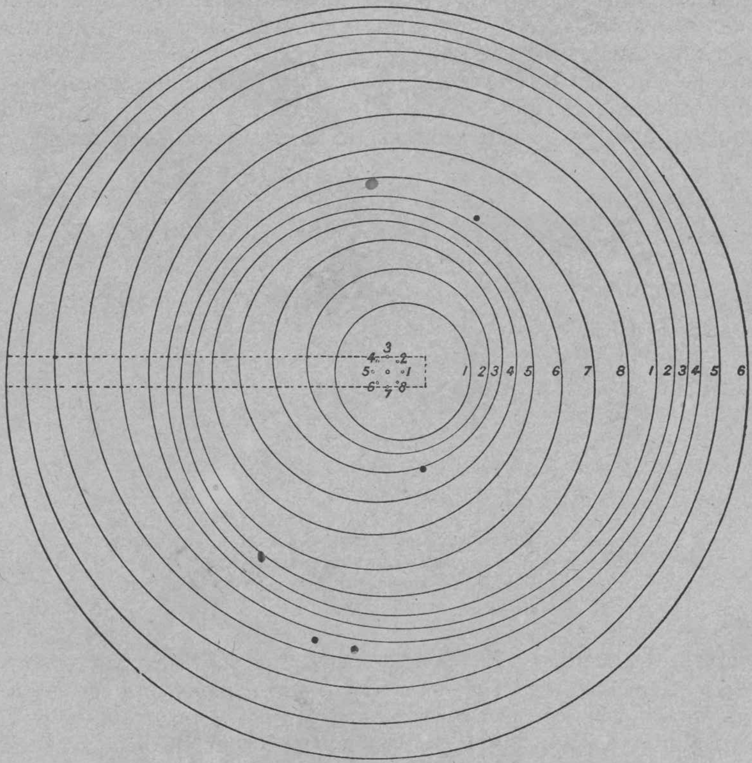

FIG. 2.—Crova's Disc. Radii of successive circles increasing by 3 mm.; drawn from 8 points round a circle of 2 mm. radius.

The Characteristics of Waves.—The characteristics of the transmission of disturbance in the form of waves are:—

1. The disturbance takes time to travel from one point to another.

2. The disturbance is propagated through a medium.

3. On meeting an obstacle the waves are reflected back, and the angles of incidence and reflection are equal.

4. The course of the waves is changed, *i.e.* they are refracted

when they pass from one medium into another in which the rate of travel is different.

5. The disturbance of a particle of the medium is alternating and not continuously in one direction. There are a series of phenomena grouped together under the terms **Interference** and **Diffraction** which can be shown to result from the alternating nature of the disturbance brought to any point by the waves.

The waves with which we are most familiar are those on the surface of water, and we may easily observe in them all the characteristics just described. It is obviously true that they take time to travel, and that the disturbance is in the medium—the water—through which they travel. The reflection of water-waves may be well seen on a reservoir when the waves come up against a straight wall. A little attention may be needed to separate the reflected from the incident waves, but with practice the two series will be seen quite distinctly travelling at equal inclinations on the two sides of the normal.

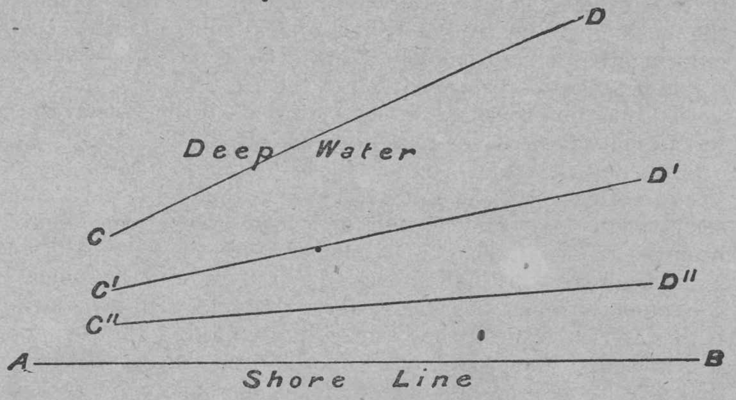

FIG. 3.—Refraction of Waves on a Sloping Shore.

Refraction occurs whenever water-waves travel obliquely towards a gradually sloping shore. The waves as they roll in become more and more nearly parallel to the shore. This may be observed on a large scale in the waves of the sea breaking on a sloping sandy shore, and on a small scale in the ripples on a pool. The explanation is to be found in the fact that as the depth decreases the rate of travel also decreases. For let AB, Fig. 3, represent the margin of the water surface, the depth gradually increasing outwards. Let CD represent a wave in deep water at a certain instant, and let the depth at C begin to diminish so as to lessen the speed of the wave. The part of the wave towards D is still in deep water, and so its speed is unchanged. A short time later, when C has reached C′, D has travelled a greater distance to D′, and so the wave has swung round. D′ now begins to travel more slowly, but C′, being in shallower water, travels more slowly still, so that while D′ travels to D″, C′ only travels to C″, and the wave swings round still more, and ultimately it may come in practically parallel to the shore-line AB.

Examples of interference of water-waves are not quite so easily detected, but one case may sometimes be seen when reflection is occurring at oblique incidence against a vertical wall. The water near the wall has a peculiar lumpy appearance, the lumps rising and falling several times in succession at nearly the same points. This appearance may be explained by the superposition and interference with each other of the incident and reflected waves.

It is easy and very interesting to study some of the characteristics of waves in the case of ripples in a shallow water-trough. Instead of looking at the ripples directly, we may illuminate the surface by a bright light—sunlight is most effective—and watch the ripples in the reflection on a suitably placed screen. Reflection may be obtained from bodies of variously shaped edges placed in the trough, and refraction may be shown by placing at the bottom of the trough bodies of lenticular or other shapes, reducing the depth from, say, 2 inches to $\frac{1}{2}$ inch, the velocity of ripple-propagation being reduced at the same time.

Turning now to sound, we shall see that all the general characteristics of waves may be recognised as—

Characteristics of Sound.—1. *Sound takes time to travel.*—We can often detect an interval between the sight and sound of some event. We see the puff of smoke from a gun before we hear the report if the gun is at a distance, or we see the steam rising from the whistle of an engine before we hear the sound, and the sound continues after the steam is shut off. Still more striking is the interval between the flash of lightning and the thunder to which the lightning gives rise. In the next chapter we shall see that direct measurements of the velocity of sound show that for a given state of the air it is constant, and that this constant value is the same as the velocity with which air-waves should travel as calculated on mechanical principles.

2. *Sound travels through air or some material medium.*—If an electric bell is suspended within the receiver of an air-pump and set ringing, the sound gradually decreases as the air is exhausted, and finally becomes inaudible, the material connection between the bell and the observer being insufficient to transmit a sensible disturbance. On re-admitting the air, the bell is heard again.

But sound may travel through media other than air. A watch placed on one end of a table may be heard ticking most distinctly on placing the ear against the other end of the table, the sound travelling through the wood of the table; or if the observer holds the watch in his teeth, he hears the ticking loudly through the teeth and the bones of the skull. The drum telephone, which consists of a couple of drum-heads with a tight string or wire connecting the centres of the two drums, is another instance of sound-propagation through a solid medium. The sound, passing through the air, strikes one drum, is conveyed from it along the string, and is finally yielded up to the air by the other drum.

Sound may easily be heard through water. If, for instance, the head is placed under water in a bath, the sound made by striking the side of the bath is perfectly audible.

3. *Sound is reflected.*—An echo is simply a case of sound-reflection, and whenever we hear one, we find some surface to which we may ascribe the reflection. On a small scale we may reflect sound by holding a watch in front of a large concave mirror. In accordance with the law of equality of the angles of incidence and reflection, the light from a source, S, Fig. 4, is gathered together after reflection at or near another point, S′. If the watch

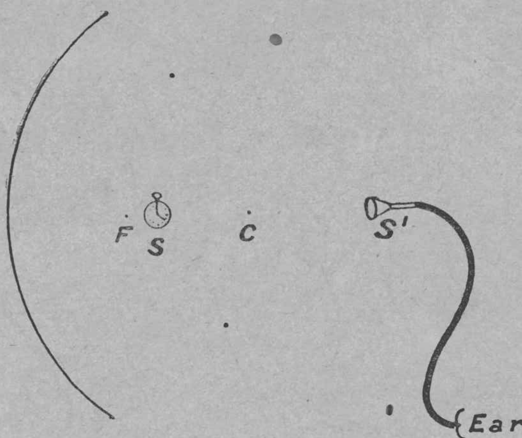

FIG. 4.—Reflection of Sound by a Concave Mirror. S, S′, conjugate foci. F, principal focus.

is placed at S, its ticking is heard most loudly when the ear is placed at S′, or, better still, when a funnel with a tube leading to the ear is placed at S′. If the watch is placed at F, the principal focus of the mirror, whence light would be reflected as a parallel beam, the sound of the ticking may be thrown across a large room.

4. *Sound is refracted when passing from one medium into another in which its speed is different.*—Sondhauss devised a sound lens consisting of a collodion balloon of lenticular shape filled with carbonic acid. Since sound travels more slowly in this gas than in air, the sound proceeding from a point at some distance on one side of the balloon and on its axis should be concentrated at a point at a certain distance on the axis on the other side, just as light would be concentrated by a glass lens, and Sondhauss verified the existence of this concentration. Fig. 5 represents the mode in

which this is explained on the supposition that the sound consists of waves. The waves diverge from the source S, and on entering the lens travel more slowly. But as the central parts reach the lens first, they are delayed more than the edges, and therefore the waves become flattened. On emergence they travel more quickly again, and the edges emerging first gain on the central part, and so give the waves an opposite curvature which concentrates them on the point S′.

Tyndall[1] describes a very interesting experiment, in which the lens is a soap-bubble filled with nitrous oxide, the source a concertina reed, and the receiver a sensitive flame.

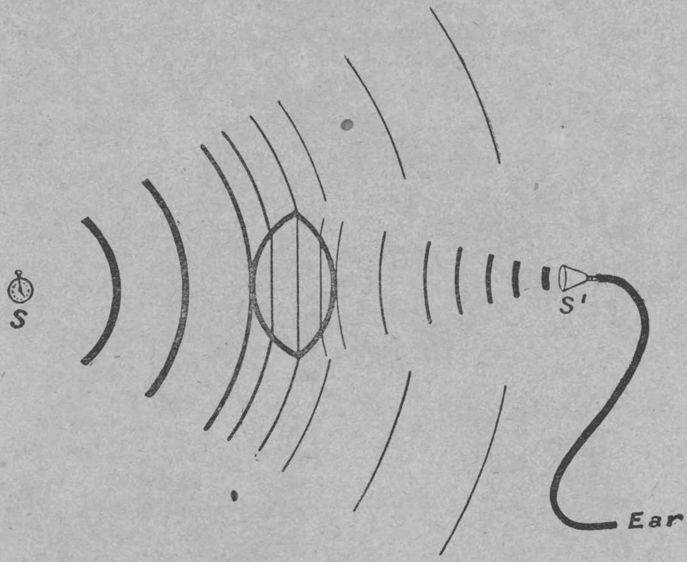

FIG. 5.—Waves Concentrated by a Lens, in which they travel more slowly. The thickness of the lines roughly represents the intensity of the waves. Radius of lens, 10; refractive index, 1·27; S S′=4f=74.

Other phenomena easily explained as cases of sound refraction will be described in Chapter II.

5. *Sound exhibits interference.*—We shall here merely mention one illustration of this, the well-known "beating" of two notes nearly, but not quite, in unison, leaving further description till we discuss the subject more fully in Chapter X.

Since, then, sound arises from vibrating bodies which must give rise to waves in the surrounding matter, and since sound exhibits all the characteristics of waves, we can come only to the conclusion that **sound consists of waves.**

The Three Characteristics of our Sensations of Sound

[1] *Sound*, 4th ed. p. 265.